

# Calibration of Regional Wave Discriminants in Diverse Geological Environments: Topographic Correlations

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Contract #F49620-94-1-0247

Sponsored by AFOSR

## ABSTRACT

• It has long been recognized that  $L_g$  waves are not observed on paths traversing oceanic crust, but this has not yet been fully explained. Using normal mode analysis and finite-difference simulations, we demonstrate that: (1) the overall thickness of the crustal waveguide affects the number of normal modes in a given frequency range; in general, thinner crust accommodates fewer modes; (2) 6-km thick oceanic crust does not allow  $L_g$  to develop as a significant phase in the frequency band 0.3-2 Hz due to the limited number of modes that exist; (3) in continental crust thicker than 15 km there are usually sufficient modes that  $L_g$  is stable; (4) the shallow sediment layer plays important roles in crustal guided wave propagation; trapping energy near the surface, separating  $L_g$  and  $R_g$  waves; (5) a 100-km long segment of oceanic structure on a mixed ocean/continent path can block P-SV type  $L_g$  propagation. The primary reason why  $L_g$  does not travel through oceanic crust thus lies in the structure of the crustal waveguide, with the decisive factor being the crustal thickness. The detailed shape of ocean to continent crustal transitions can influence  $L_g$  blockage, but the general inefficiency of  $L_g$  propagation in the oceanic structure is the dominant effect.

• Regional P and S waves decay with different rates due to complex geometric spreading and attenuation factors, hence discriminants based on P/S ratios are distance dependent. In a region without  $L_g$  blockage, the distance dependence,  $\gamma$ , of  $P_g/L_g$  ratios and the factors influencing the distance dependence are of concern for the correction of the path effect. 80 earthquakes in the Western U.S. recorded at four stations of the Livermore NTS Network are used to determine the regional distance dependence of  $P_g/L_g$  ratios.  $\log P_g/L_g$  is found to be significantly correlated with both propagation distance and surface roughness. The correlation is strongest when the product of distance and roughness is used as an independent variable. The distance dependence  $\gamma$  can be approximately expressed as a linear function of surface roughness. The ratio data in the frequency range 2.0-6.0 Hz have the most distance dependence. Corrections based on the inferred relations for distance and roughness can reduce the variance of the discriminant  $\log P_g/L_g$  by 20%. Analysis of the  $P_n/L_g$  ratio is underway.

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## **OBJECTIVE:**

This research is directed at improving the performance of regional wave discriminants by developing empirical and, potentially, theoretical wave propagation corrections for  $P_g/L_g$  and  $P_n/L_g$  ratios, as well as for  $L_g$  amplitudes. It will hopefully provide fundamental advances in our understanding of the regional wavefield. The basic idea is that by establishing the influence of large-scale crustal waveguide structure on the amplitude ratios of regional phases, the scatter in those ratios can be reduced, thereby enhancing the discriminant performance. We have explored the influence of irregularities in the crustal waveguide, such as surface topography, bathymetry characteristics, Moho depth, sediment depth, and attenuation term in the first year of the project. In the second year, a numerical simulation study has been undertaken to understand the role of crustal thickness in propagation of  $L_g$  waves. We are also studying the variation of  $P_g/L_g$  and  $P_n/L_g$  with distance and surface roughness.

## **RESEARCH ACCOMPLISHED**

We have carried out two projects:

### **Why the $L_g$ Phase does not Traverse Oceanic Crust**

$L_g$  only propagates in continental crust. The dominant opinion has been that the disappearance of  $L_g$  in oceanic regions might be due to the effect of propagation across a continent-ocean margin. If this is the main reason, the structure of the continental margins would play a more important role than the structure of the oceanic crust itself in disrupting  $L_g$  propagation. Our previous work has established that there is significant correlation between regional phase amplitude ratios and minimum crustal thickness along some propagation paths (Zhang and Lay, 1994ab; Zhang et al., 1994). This motivated us to explore the role of crustal thickness in guided wave ( $L_g$ ) propagation, which may help us understand the observed phenomena related to path effects (Zhang and Lay, 1995). Because  $L_g$  can be viewed as the sum of higher Rayleigh and Love modes, we use a normal mode method to construct dispersion curves for Rayleigh waves in layer over a halfspace models with various crustal thickness (Figure 1). It is conspicuous that the number of normal modes in the 0-2 Hz range decreases for thinner crust. For a 32-km thick crust (Figure 1a), the group velocity minima (or Airy phases) concentrate within a narrow group velocity range between 3 and 3.5 km/s. The concentrated  $L_g$  phase develops by constructive interference of these higher mode Airy phases. According to our finite difference calculations, there is significant energy within the " $L_g$  window", marked by the two lines in Figure 2 for both radial and vertical components. However, there are only 5 modes for the 6-km thick (oceanic) crust in the same frequency range (Figure 1d). The synthetics shown in Figure 3 illustrate that there is almost no energy within the  $L_g$  window, due to the limited number of modes that exist in the thin oceanic crust. Our calculations indicate that the lack of  $L_g$  signals for oceanic paths is primarily a gross structural effect, intrinsic to the thin waveguide. Zhang and Lay (1995) also shows that  $L_g$  and  $R_g$  waves are separated in the time domain given the existence of a low-velocity sediment layer. Two-dimensional models show that a 100-km long segment of oceanic crust can reduce  $L_g$  amplitudes significantly, whereas a 50-km long segment does not. This phenomenon can be simulated without having to introduce a water layer, as did Cao and Muirhead (1993).

### How P/L<sub>g</sub> Ratios Change with Distance and Surface Roughness

In regions with crustal structures that cause L<sub>g</sub> blockage, P/L<sub>g</sub> ratios can change drastically on some propagation paths, and one must correct for, or at least recognize this effect. In regions without L<sub>g</sub> blockage, the distance dependence of P/L<sub>g</sub> ratios and the factors that influence distance dependence should be corrected for. We chose 80 earthquakes in the Western U.S. recorded at four stations of the Livermore NTS Network to determine the distance dependence of P<sub>g</sub>/L<sub>g</sub>. No L<sub>g</sub> blockage is observed in this region, even in areas with strong relief like near the Sierra Nevada Mountains and Death Valley. Log P<sub>g</sub>/L<sub>g</sub> ratios are calculated following Lynnes and Baumstark (1991). Figure 4a shows the result obtained in the 2-4 Hz band. CC means correlation coefficient, SIG standard deviation, and SLO the slope of the regression line. Following Baumgardt and Der (1994), we assume

$$R(\Delta) = 10^{\gamma\Delta} \quad (1)$$

where R is the P<sub>g</sub>/L<sub>g</sub> ratio,  $\Delta$  the distance in unit of km,  $\gamma$  the slope of the regression line. It is interesting that while log R increases with  $\Delta$  at frequencies higher than 1 Hz, it decreases at low frequency (0.3-1.0 Hz). The low frequency result is not shown here, but the results of all regressions for different frequency bands are summarized in Figure 5. Figure 5a shows that the slope for the low frequency band is negative, contrasting with the positive slopes at higher frequency bands.

Previous work has indicated that surface topography may provide a surrogate for crustal variations that influence regional phases. log R correlates with RMS surface roughness over the path almost as strongly as with distance. The 2-4 Hz band result is shown in Figure 4b. Figure 5c is a summary of the correlation coefficients of log R with distance (hollow circles), roughness (hollow triangles), and their product (solid squares) for 6 frequency bands. The slope of log R vs. roughness in the low-frequency band is also negative, this is consistent with our observation based on the data from Semipalatinsk, Kazakhstan (Zhang and Lay, 1994a). Although the correlation patterns of Figure 4a and 4b are similar, the two independent variables distance and roughness are not correlated. Their correlation coefficient is only 0.08.

We consider an end-member case in which the distance behaviors of P<sub>g</sub> and/or L<sub>g</sub> are controlled by path roughness. Taking the simplest assumption, we let  $\gamma$  be a linear function of roughness, i.e.

$$\gamma(\mu) = \alpha\mu \quad (2)$$

where  $\mu$  stands for roughness,  $\alpha$  is a proportional coefficient. Then (1) becomes

$$R(\Delta) = 10^{\alpha(\Delta\mu)} \quad (3)$$

In actuality, we expect that  $\gamma$  involves contributions from intrinsic attenuation, scattering and geometric spreading, but the separate contributions are very difficult to isolate. Figure 4c reflects the correlation of log R with the product of distance and roughness. The correlation coefficient is higher than that of each variable respectively (solid squares in Figure 5c). The slopes ( $\alpha$ ) for various bands are summarized in Figure 5b. Figure 5d illustrates the variations of another parameter, coefficient of determination, which is interpreted as the proportion of the variability of the data explained by the regression on the independent variable (see Zhang et al., 1994). The product of distance and roughness (solid squares) explains more variability than either distance (hollow circles) or roughness (hollow triangles) alone.

In the frequency range 2.0-6.0 Hz log R shows the greatest distance and roughness dependence. Thus the correction for the two variables and their product in this range produces more reduction in the variances of log R data than in other frequency range.

### CONCLUSIONS AND RECOMMENDATIONS:

Finite-difference and normal mode calculations for simple crustal models clearly demonstrate that waveguide structure, especially the overall thickness of the crust and the presence of any low-velocity surface layer, strongly affect the propagation of regional waves like  $L_g$  and  $R_g$ . The correction based on distance and roughness dependence of the  $P_g/L_g$  ratio can reduce the data variance up to 20%. This correction may improve practical discrimination. A discrimination test between NTS explosions and Western U.S. earthquakes will be performed to verify the effect of correction for propagation distance and surface roughness. A regression study on the  $P_n/L_g$  ratio is being performed. To obtain more insight into the observed patterns, simulations with reflectivity and finite difference methods are to be done in the near future.

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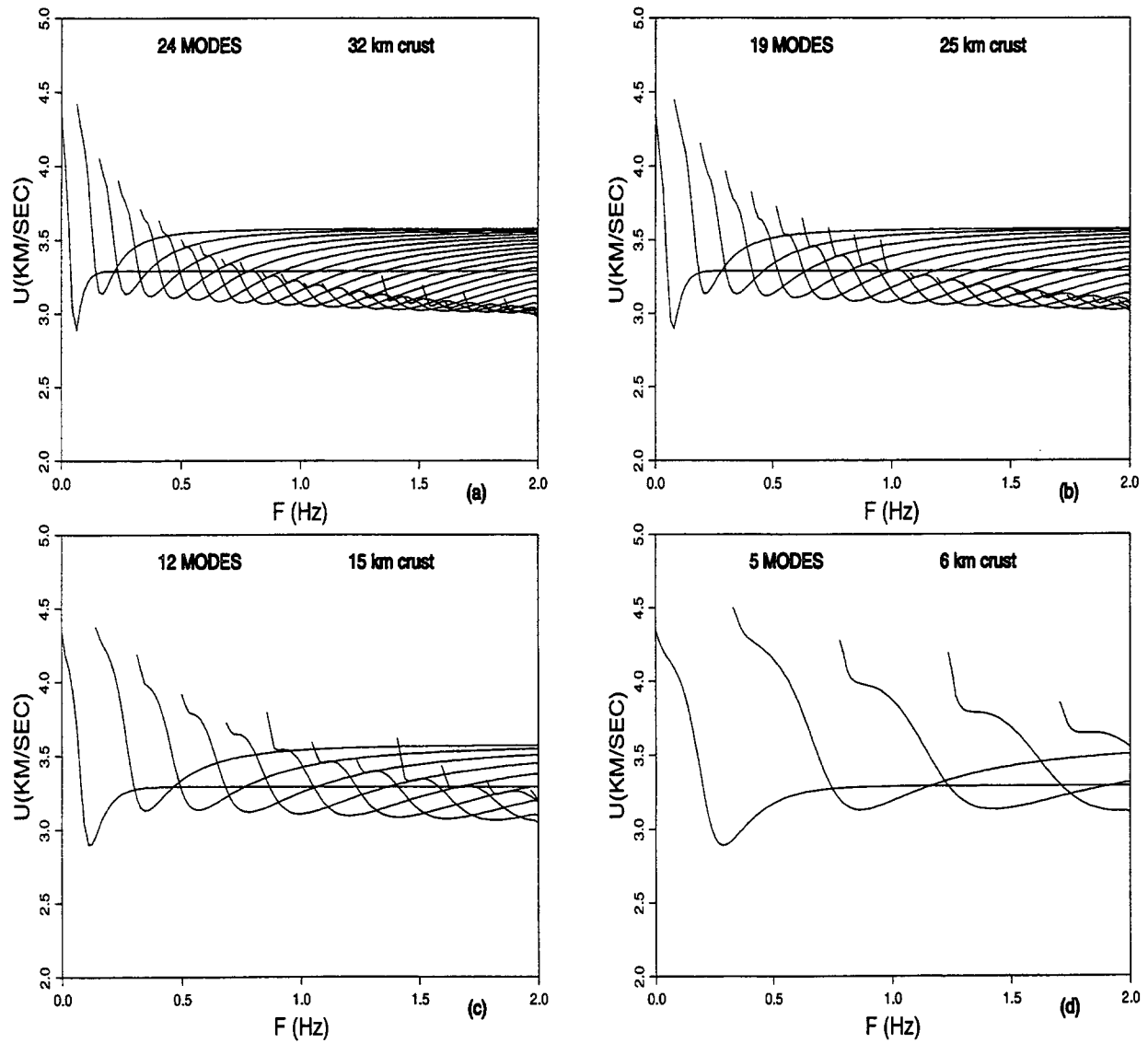


Figure 1: Dispersion curves for Rayleigh waves in layer over a halfspace models with crustal thickness of (a) 32 km, (b) 25 km, (c) 15 km, and (d) 6 km.  $U$  stands for group velocity. The number of normal modes in the 0-2 Hz range decreases for thinner crust.

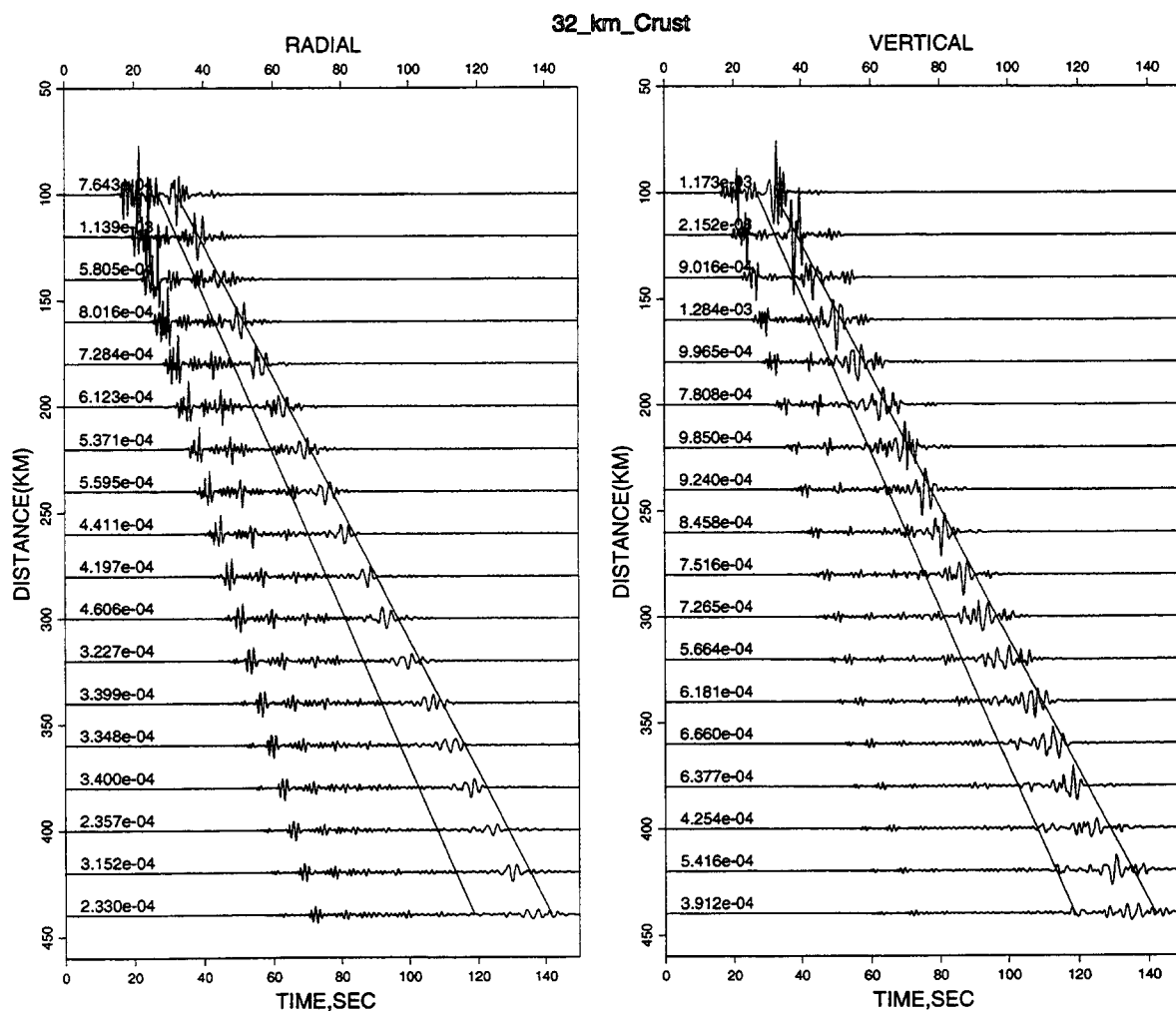


Figure 2: Synthetic seismograms for a layer over halfspace model with 32 km thick crust. Both radial and vertical components are shown. Two lines mark the group velocity window 3.7-to-3.1 km/s used for calculation of RMS  $L_g$  amplitudes (called the  $L_g$  window). The RMS amplitude values in the  $L_g$  window are shown for each waveform.

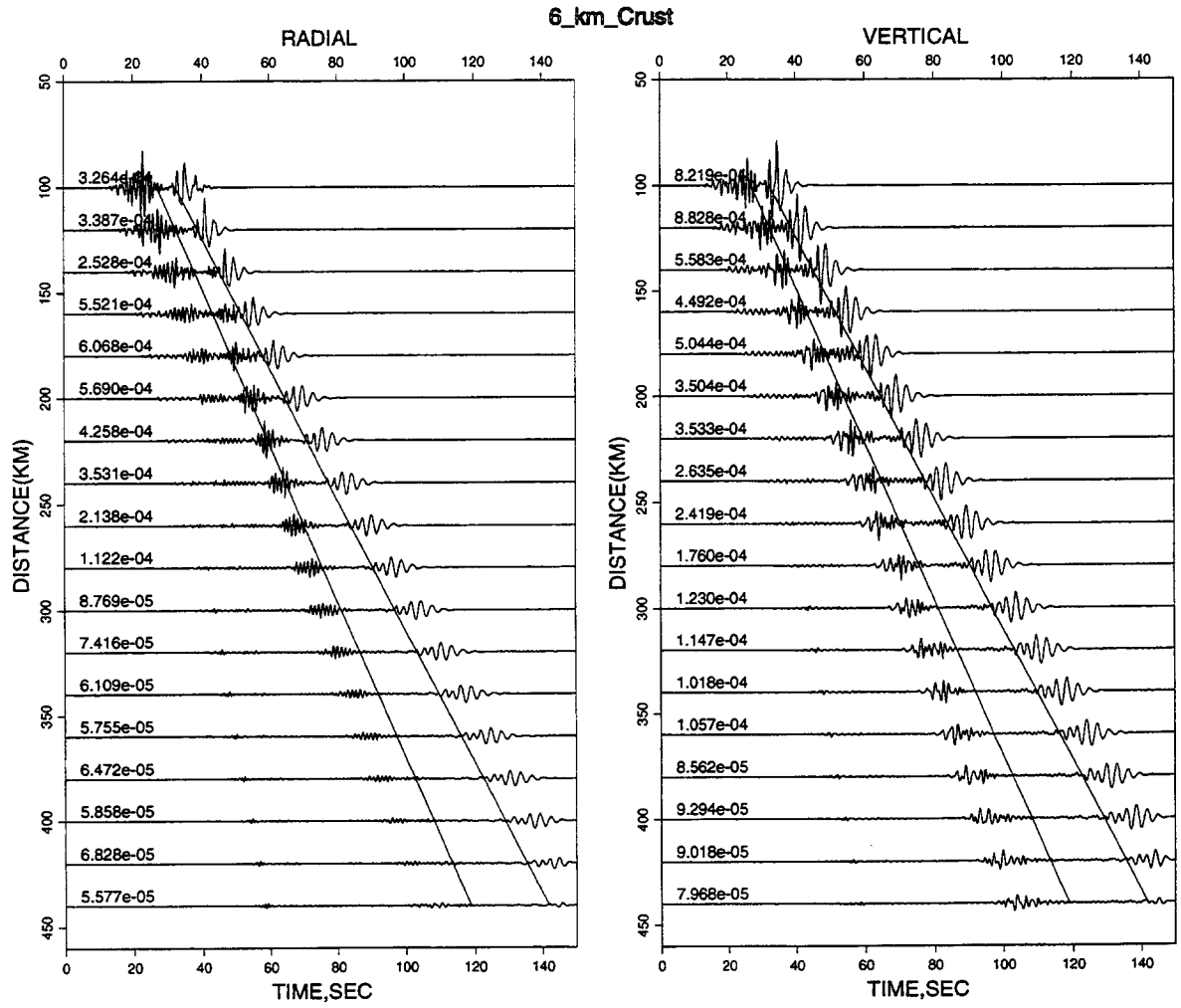


Figure 3: Synthetic seismograms for a layer over halfspace model with 6-km crustal thickness. The arrivals within the  $L_g$  window are weak. The  $R_g$  waves are delayed, and most of their energy is outside the  $L_g$  window.

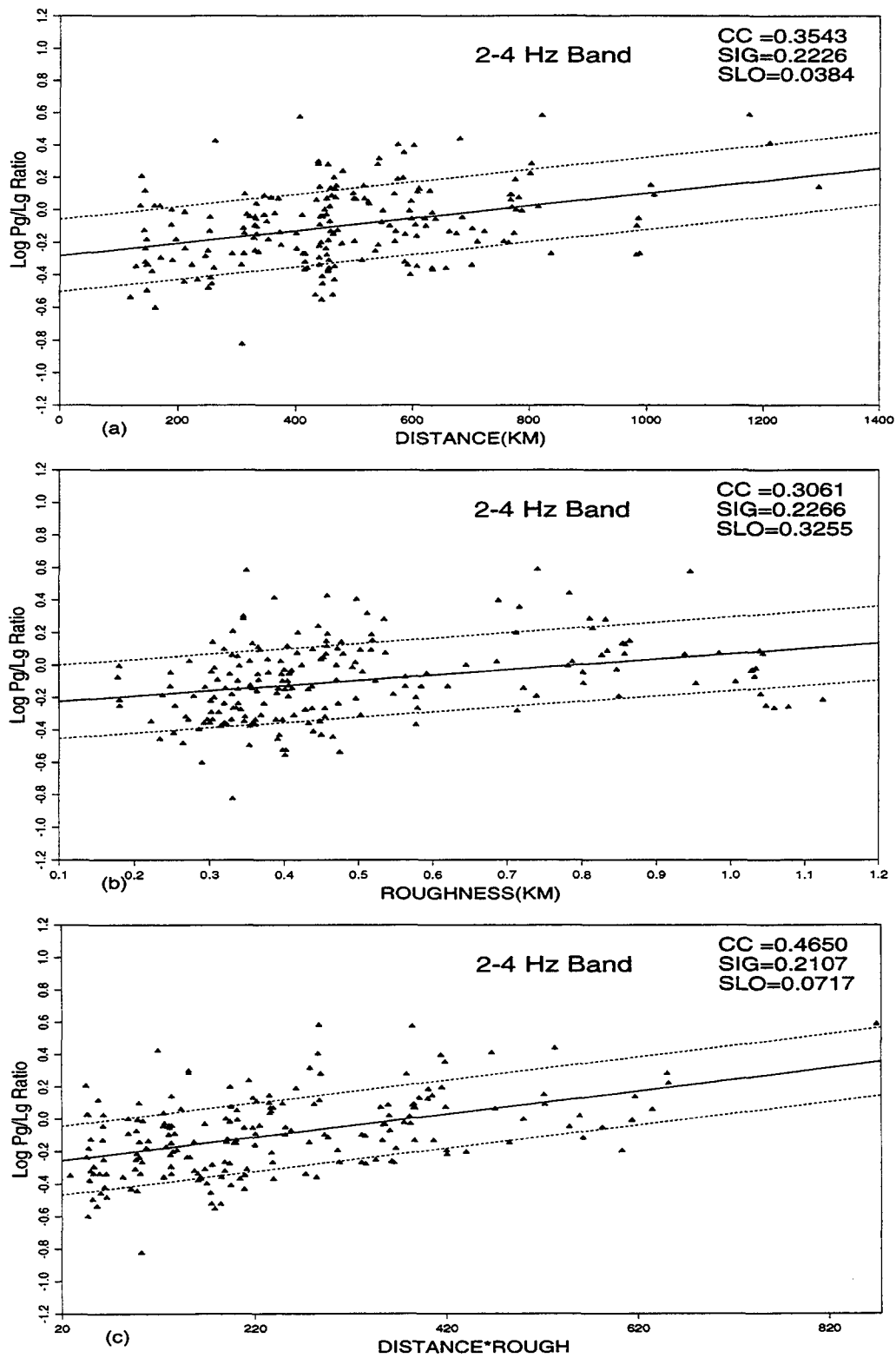


Figure 4:  $\text{Log}(P_g/L_g)$  as a function of (a) distance, (b) roughness, and (c) distance\*roughness for Western U.S. data in the frequency band 2-4 Hz.

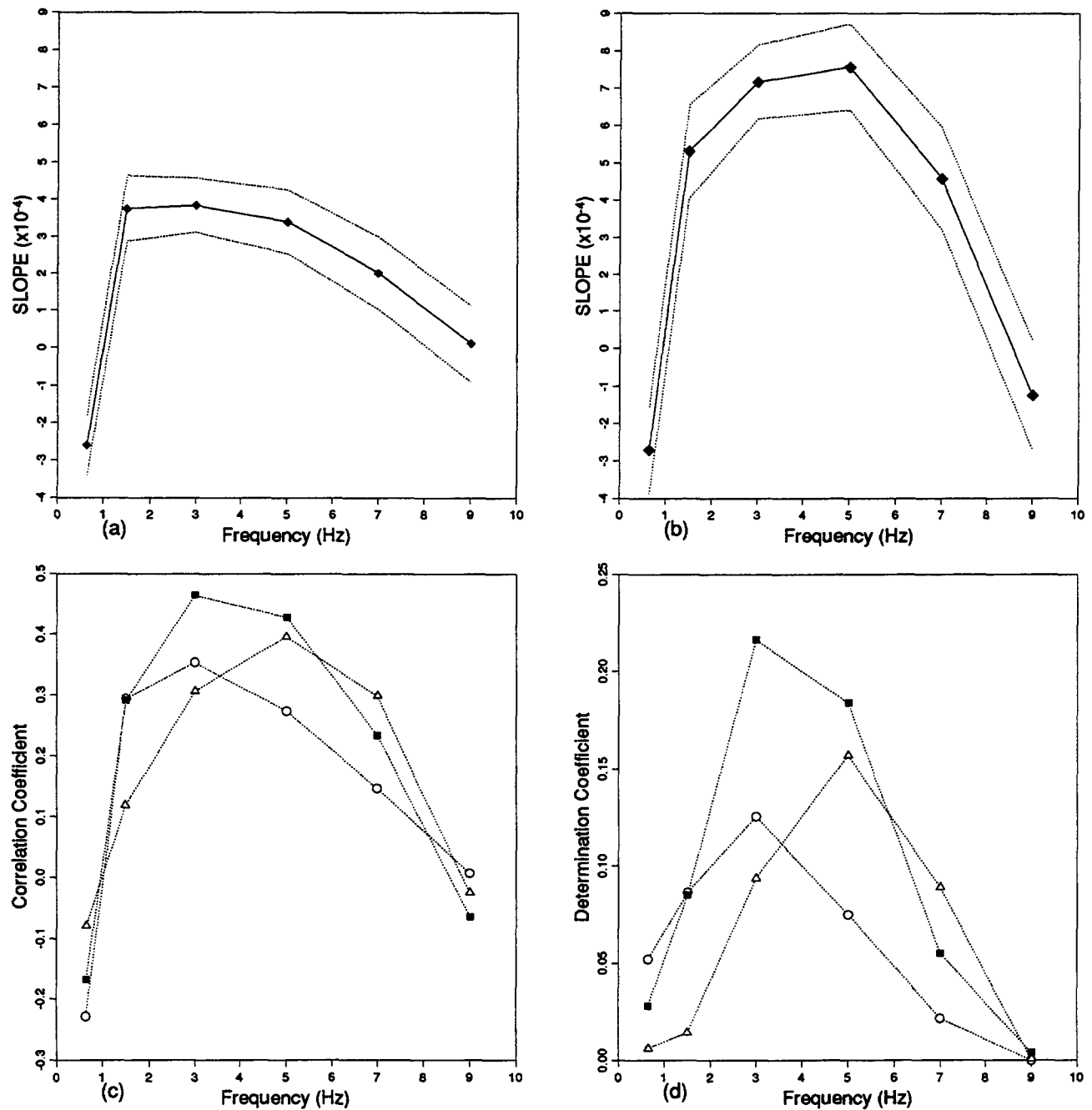


Figure 5: Summary of the correlation results of  $\log(P_g/L_g)$  with distance, roughness, and distance\*roughness. (a) shows the slopes of the fitting lines of  $\log(P_g/L_g)$  with distance in various frequency bands. (b) shows the slopes with distance\*roughness. (c) the correlation coefficients of  $\log(P_g/L_g)$  with distance (diamonds), roughness (triangles), and distance\*roughness (squares). (d) the coefficients of determination of the regressions of  $\log(P_g/L_g)$  with distance (diamonds), roughness (triangles), and distance\*roughness (squares).